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D2D: A ROBUST TECHNIQUE FOR DETECTION OF STRUCTURAL HETEROGENEITIES IN SOLIDS, BASED ON TRANSIENT THERMOGRAPHY

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INTRODUCTION

A sensitive aspect of thermal techniques is represented by the very nature of the involved (thermal) stimulus. It is very easy in effect to encounter parasitic (unwanted) heat sources in a thermal measurement [1], which at the end contribute to worsten the signal to noise ratio. This means that applying thermal techniques in field environment is far more difficult than in environments where heat sources are well under control (typical laboratory environment). Special techniques have to be used in such situations to eliminate the parasitic sources effects in order to ensure the repeatability of the measurement, that is the capability of the technique to yield the same results from the same specimen in different working conditions, or in other words making the technique practically usable.

D2D (Defect To Direction) is a new transient thermography technique which has been developed with field usability as main concern. D2D addresses mainly the elimination of parasitic heat source effects issue. Besides that, D2D addresses also other questions like real-time capability, large surface exploration, low off-line post-processing, etc., which are implied by field usability requirement.

PRINCIPLE OF D2D

Fig.1 shows the basic setup. A 1D (linear) heater is placed above the specimen and moved in a plane parallel to specimen's surface in a direction almost perpendicular to heating line. A thermal imager is tied to the heater in such a way that each surface element travels in its field of view for a certain time after heating and its evolution is recorded in a sequence of thermograms.

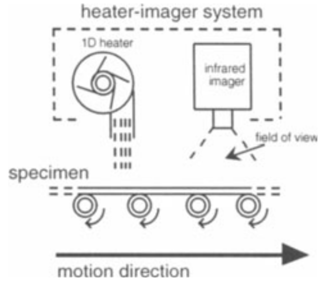


Figure 1. D2D experimental setup.

Due to the applied motion, any thermal phenomenon on the specimen's surface will translate into a corresponding trajectory in the IR images stack. Trajectories are divided into 2 classes: 1) Heat source trajectories: these are due to the motion of heat sources in the imager's field of view; 2) Heat source effects trajectories: these are due to the response of specimen's structure to the thermal stimulus produced by the heat source traveling above its surface. Isolating class 2 trajectories in the IR images stacks from the global information will therefore lead to the pure structure response of the specimen under test.

Let us consider a surface element S of the specimen and pixel P which represents S in the thermal image (Fig.2). If a controlled motion is applied to the specimen with respect to the heater-imager ensemble, pixel P will follow a predictable trajectory. If a defect is lying in or beneath S, its effect will appear in S with a certain time delay depending on the physical properties of the specimen (defect depth, material diffusivity, etc.). But indipendently of this time delay, these effects will be lying nowhere else than on the trajectory of pixel P (class 2) also called "Preferred Direction". This is true for any heat source acting on the surface, including main heater. If the source does not transfer energy to the specimen then only the corresponding trajectory (class 1) will be visible in the thermogram stack; in the other case, that is if heat source is strong enough to provoke the underlying structure response, besides the source trajectory (class 1), there will be a source effects trajectory (class 2) in the preferred direction along which the structure respose will be lying and only the latter one will be taken into account in the structure detection process.

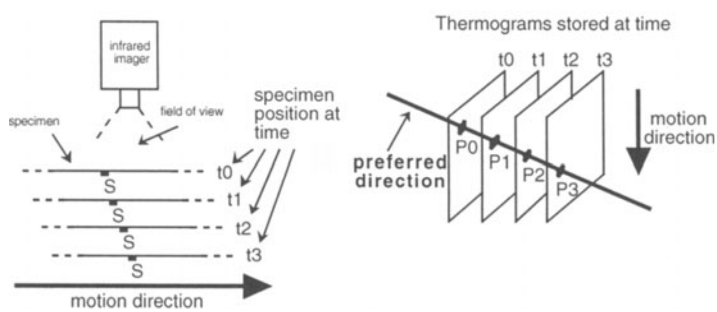


Figure 2. Relation between surface element displacement and preferred direction identification inside IR image stack.

As a conclusion it can be stated that, provided that a sufficient amount of thermal energy is transferred to the specimen, to isolate real defects from apparent ones it will be sufficient to evaluate the time evolution of the pixels along their trajectory in the thermogram stack. As the simplest motion applicable to the specimen is linear (constant velocity), the related trajectory inside the thermogram stack will be represented by an oblique line whose direction is the preferred direction. That is where D2D name comes from: Defect To Direction. (As a matter of curiosity, an accelerated motion at a constant frame acquisition rate would translate in a parabolic trajectory inside the thermogram stack, etc.).

HEAT SOURCES BEHAVIOUR

Various possible cases are shown in Fig.3. TrPD represents the preferred direction, that is the direction in which effects (if any) from the heated structure will evolve. Tr1, Tr2, Tr3, Tr4 and Tr5 (class 2) represent the trajectories of a heat source moving respectively at a higher, equal, lower, null and negative relative speed with respect to specimen than the main heater-specimen relative speed. Tr2 is horizontal and is active all the time in the same region of the imager's field of view. Practically it represents heat sources tied to main heater as can be spurious sources due to main heater mechanical distortions, uneven pose, etc. Tr4 represents the trajectory of a heat source is tied to the specimen. In this case the source is active all the time in the same region of the specimen's surface and its trajectory is the same as the preferred direction. Also the eventual effects on the underlying structure will lie in the same direction. This is typical of environment generated heat sources when the specimen is fixed and the heater-imager setup travels along its surface as in the case of large specimens like airplane wings, fuselages, etc. Tr1eff, Tr2eff, Tr3eff, Tr4eff, Tr5eff (class 1) represent the effects of these heat sources when they pass over a heat-absorbing surface element of the specimen.

DISCRIMINATION CAPABILITY OF D2D

D2D 's discrimination capability depends on the power of its directional operator to enhance the signals in one direction (the preferred direction) against signals in any other direction in the thermogram stack. A variety of operators can be used, provided that they are applied in the preferred direction.

A simple integrator has been chosen as directional operator. The directional integrator will not reduce the parasitic heat sources contributions, but will rather enhance the specimen's structure response. This means that the resulting reconstructed thermal maps will not be flat: they will show instead strong deformations in the background signal, but still with an enhanced signal to noise ratio. It will be then necessary to apply particular background elimination operators in order to obtain flat images with bumps only where structural inhomogeneities are present.

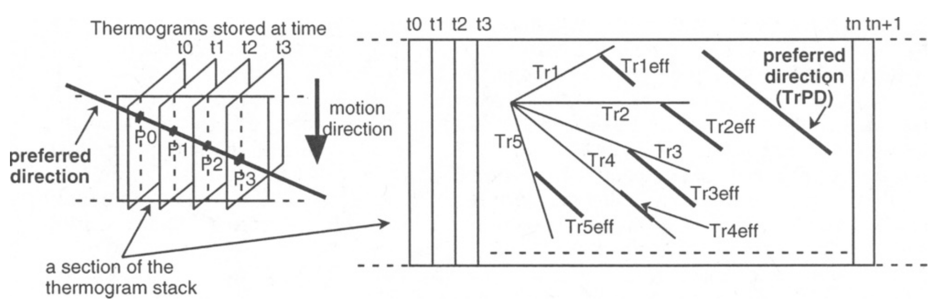


Figure 3. Heat sources: Trajectories and effects on a section of IR images stack.

A noise source which is intrinsecally reduced by directional integrator is the high frequency noise produced either by the IR imager itself or by the vibrations of the imager-heater equipment. Vibrations may arise from the motion of the imager-heater over the specimen's surface, in case of non-solid state heaters (for example hot air guns) rigidly joined to the imager, etc.

TOMOGRAPHIC CAPABILITIES OF D2D

The evolution of any pixel is recorded while it travels in the field of view of the thermal imager. Any defect, if present, will appear on the surface of the specimen and therefore recorded with a delay depending on its physical characteristics (mainly defect depth and material diffusivity) [2]. This means that not all the trajectory along the preferred direction in the IR images stack will necessarily carry valuable information about the defect. If the directional integration operator is applied to a certain subset, the resulting reconstructed map will contain only the defects that have appeared to the surface and recorded in the thermograms belonging to that subset. If for example only the first thermograms are considered, the resulting reconstructed map will show only the shallow defects whilst if the last thermograms are considered, only the deeper defects will be shown. Considering all the thermograms will yield to a thermal map containing all the embedded defects of the specimen. On the opposite side, if only defects at a certain depth are to be detected (eliminating therefore all the eventual contributions due to shallower and deeper layers), it will be sufficient to apply the directional operator only to the corresponding stack subset. An example will be shown in the next paragraphs (Fig.6,7,8).

D2D BASIC SETUP AND TUNING

To get the time evolution signal of the entire specimen's surface in the same conditions (delays, acquisition time, etc.), heater and imager have to be tied together. A relative velocity with respect to the specimen has then to be applied to the heater imager ensemble in order to explore the entire surface (Fig.2). In a laboratory setup the dimensions of the specimen under test are reduced so that heater and imager are held fixed and specimen is moved with respect to them. In a field setup and/or with a large surface to be explored, (airplane wings, frescoed walls, etc.), specimen is fixed and heater-imager are moved above the surface.

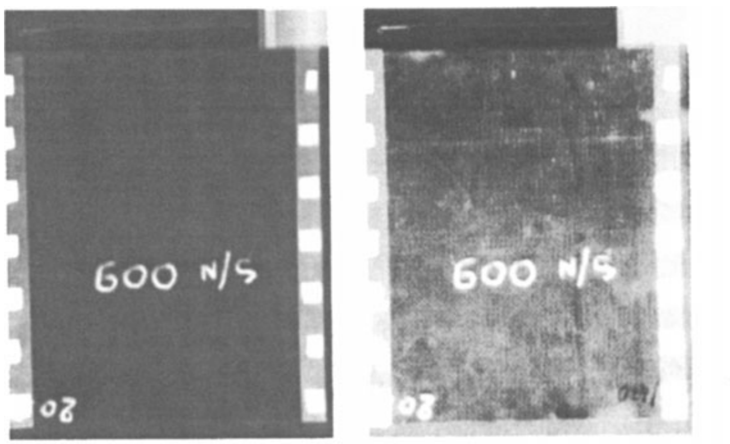
The essential point in tuning up D2D is to have the defect evolution fully included in the thermogram stack which means that pixel P representing surface element S has to stay in the field of view for all the thermal evolution of S. Distance between heater and imager's field of view is set in such a way that defect effect appears a little after S enters in the field of view (distance is related to defect depth). Velocity is set in such a way that defect effect disappears a little before the corresponding surface element quits the field of view (motion velocity is related to material diffusivity). Thermogram acquisition rate is set in such a way that the resulting stack is composed by a sufficient number of thermograms in order to be able to reconstruct the defects map. A low acquisition rate will yield to a poor signal to noise ratio; a high acquisition rate will yield to an excessive number of thermograms thus to a higher processing power. The last parameter is the preferred direction which conceptually can be identified knowing all the geometrical characteristics of the data acquisition system. However this is not an easy task especially when the the pixel-to-distance conversion factors are not well known due to eventual perspective distortions introduced along the optical path in the experimental setup. A typical case of perspective distortion is when mirrors are required to redirect the field of view to an otherwise unreachable surface, or when the IR imager has to be tilted, etc. Moreover these distortions are not generally maintained in different data acquisition sessions. The easiest way is therefore to identify the preferred direction directly in a section of the stack made of the same column of all the IR images. A practical example is shown in Fig.5 and commented in the related paragraph.

EXPERIMENTAL SETUP

A 30x30 cm square, 5 mm thick CFRP plate (Fig.4a,b) made of 25 carbon fiber plies placed at 0-90° has been used. Nine square defects (80 μm teflon) have been embedded with 12, 6 and 4 mm side length at 0.25, 1.25 and 2.5 mm depths. Specimen was fixed to an x-y table. The motion velocity was 2 cm/sec. The heater was a home made hot air linear heater powered by two aligned motors of different power. Total heating power was 1000 W and heating coil was picked out from an old owen. The thermal imager was a liquid nitrogen cooled Thermovision® 900 equipment manufactured by AGEMA Infrared Systems (Sweden). Thermograms were collected at a rate of 15 per second.

RESULTS

A sequence of 300 thermograms was acquired with specifications listed above. A pixel stayed in the imager's field of view for about 121 thermograms. Preferred direction was identified directly on a section of the stack (Fig.5) made of the same column of all the thermograms. The preferred direction is clearly visible and also



a. B/W picture.　　b. Equalized B/W picture.

Figure 4. Pictures of the CFRP plate

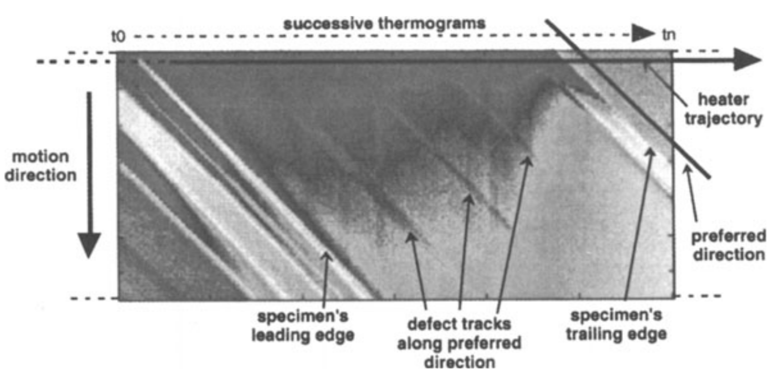


Figure 5. A section of IR images stack.

the patterns generated by 3 defects. The triangular zones at both left and right sides are relative respectively to the field of view not yet occupied by the specimen and to the field of view already left free.

Directional integrator has been applied to 3 subsets of the stack and the reconstructed maps are shown respectively in Fig. 6, 7 and 8. Image processing techniques like contrast enhancement, X-gradient and Y-gradient have been used to enhance the maps. Three subsets (1-10, 50-100, 1-100) of the thermogram stack were considered. In subset 1-10 (Fig.6a,b,c), only shallow structural elements are visible (writings, shallow defects, superficial scratches and surface texture details). In subset 50-100 (Fig.7a,b,c), shallow defects have disappeared (scratches, texture details and writings) while 4 deeper defects have appeared. In subset 1-100 (Fig.8a,b,c), almost all the elements present in subsets 1-10 and 50-100 are clearly visible with a normal enhancement of the shallow ones with respect to the deeper ones. The deepest defects are still present in subset 1-100 but not much visible as in subset 50-100 because of the normalization introduced by the shallower ones. Fig.9 represents the same picture as Fig.6b in a 1:1 scale. The remarkable definition of surface texture detalis can be noted when compared with the B/W picture of the specimen shown in Fig.4b.

a) Contrast enhancement　　　b) X gradient　　　c) Y gradient

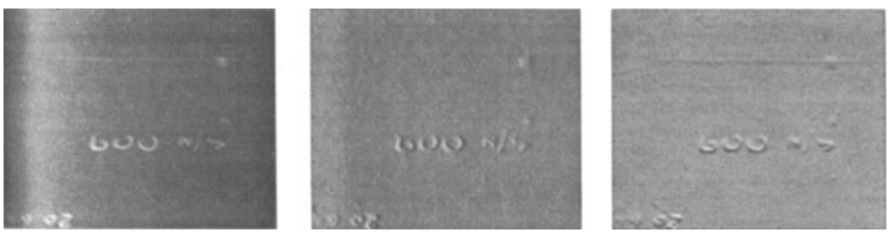


Figure 6a,b,c. Directional integrator applied to thermograms subset 1-10.

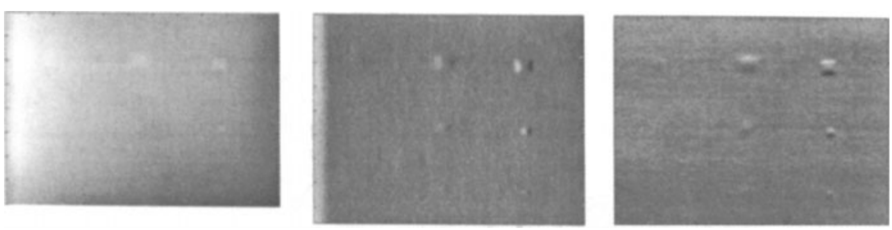


Figure 7a,b,c. Directional integrator applied to thermograms subset 50-100.

Figure 8a,b,c. Directional integrator applied to the entire thermograms set 1-100.

In this experiment the heater had a strong spatial unevenness due to uneven power distribution in the air fans. A lighter vertical stripe can be observed in Fig.6a due to heater unevenness, immediately after heating (first 10 thermograms => 3 seconds after heating). Fig.7a and 8a show the edge effect distortion 10-12 seconds after heating.

MEETING THE ADDITIONAL SPECIFICATIONS

A field-usable technique has to be insensitive to parasitic stimuli, should not require extensive care in setting up the data acquisition system, should require almost no decision during acquisition, and possibly yield results in real time.
D2D meets these specifications in the following way:

1 - Real time capability. D2D is a pixel based technique. Surface elements remain in the imager's field of view for a time depending on the selected velocity. As soon as they leave the field of view, they can be processed. There is no need to wait for pixels from other regions in order to do the processing.
2 - Large surface exploration capability with no offline image processing. The width of the surface to be explored is limited by either heater length or field of view. The length is in principle unlimited. As long as the heater-imager setup moves over the specimen, data continue to be acquired and processed.

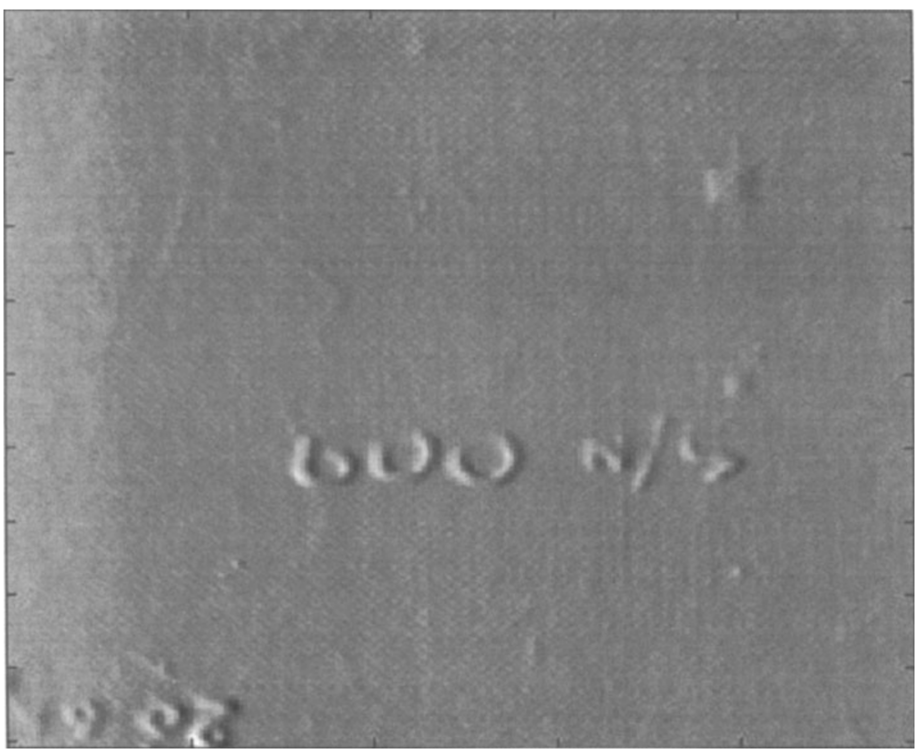


Figure 9. X-gradient filtered reconstructed map. Directional integrator has been applied to thermogram subset 1-10. Shallow defects and surface texture details are visible.

3 - Decision-free operation (no skilled personnel required). No operator action is required other than selecting the preferred direction to follow in the thermogram stack at the very beginning of the data acquisition session. Even this can be done automatically provided that every element is known in order to convert heater-centered coordinates system into imager-centered coordinates system. Another solution could be using markers sticked on the surface producing a signal along the preferred direction easy to be treated automatically by a simple image processing algorithm.

4 - Small care in setting up the data acquisition system. D2D can be considered pixel based as long as the energy amount received by any surface element do not induce thermal processes in the neighbouring surface elements, that is there has to be no cross-talk between unevenly heated surface elements so that the induced processes can be considered 1D processes. This means that slight heating unevenness due either to the heater itself (skewness with respect to the surface or heating unevenness) or to the specimen itself (surface curvature, etc) will not jeopardize the results. The practical interest of the robustness against uneven heating is that D2D will still yield comparable results even if heater pose is not the same during different acquisition sessions and that no extreme care has to be taken in setting up the whole equipment.

5 - Very low false call / missed defect probabilitiy. Provided that sufficient amount has been transferred to the specimen, if a pattern appears along the preferred direction then this pattern represents a defect (zero false calls). Conversely, if nothing appears in that direction, then there is no defect (zero missed defects).

CONCLUSION

It is quite difficult to know if the read-out from a classical transient thermography experiment is due to the underlying structure or to an external heat source or to both in which percentage. D2D has introduced the concept of "Preferred Direction" which determines where and when in the collected data the valuable information is stored. Very promizing results have been obtained from a real CFRP plate through data acquisition sessions made in field environment.

All tests were made by applying a very simple operator (integrator). Different operators can be selected on the basis of which kind of structure information has to be extracted.

Future work includes the development of new operators for the evaluation (size and depth) of the defects.

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